Naturally better

Science and technology are looking to nature's successful designs for inspiration

Biologists often find themselves awestruck by the elegant perfection of living organisms. From the sophisticated ventilation system of a termite mound to the tensile strength of spider silk, nature has invariably selected the most effective designs through billions of years of relentless evolutionary pressures. From molecules to organisms, scientists and engineers have repeatedly been enthralled by nature's handiwork and have emulated natural designs in man-made innovations.

A range of technological advances have been inspired by living organisms and examples of biomimicry now include synthetic materials with new mechanical properties that emulate mollusc shells, bones or sponge spicules; self-cleaning surfaces that copy the microstructure of lotus leaves; an echoreceiver for shallow-water operation modelled on dolphin sonar; and new photovoltaic techniques inspired by photosynthesis.

"Technical solutions to problems usually optimize existing concepts as can be seen, for instance, in the development of the Otto engine, which has practically remained unchanged for a hundred years," said Ralph Spolenak, Chair of the Laboratory for Nanometallurgy at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. "If one wants to make big steps forward, one has to think out of the box and try completely new concepts. Natural solutions may, in this regard, be used as inspiration for new technological solutions."

> **"This is the real news of biomimicry: after 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to survival."**

Scientists and engineers who emulate nature's designs often ascribe to the insights of science writer and conservationist Janine Benyus—probably the most popular and influential herald of biomimicry. Educated as a forester, Benyus wrote her book, *Biomimicry: Innovation Inspired by Nature*, in 1997 and it has subsequently become a roadmap for the growing biomimicry community (Benyus, 1997). Benyus's message is clear and straightforward. "The core idea is that nature, imaginative by necessity, has already solved many of the problems we are grappling with," she wrote on the website of the Biomimicry Institute (Missoula, MT, USA; www.biomimicry.net), of which she is Board President. "Animals, plants, and microbes are the consummate engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth. This is the real news of biomimicry: after 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to survival." Benyus maintains that biomimicry might be the best path to a better future for mankind: "The conscious emulation of life's genius is a survival strategy for the human race, a path to a sustainable future. The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone."

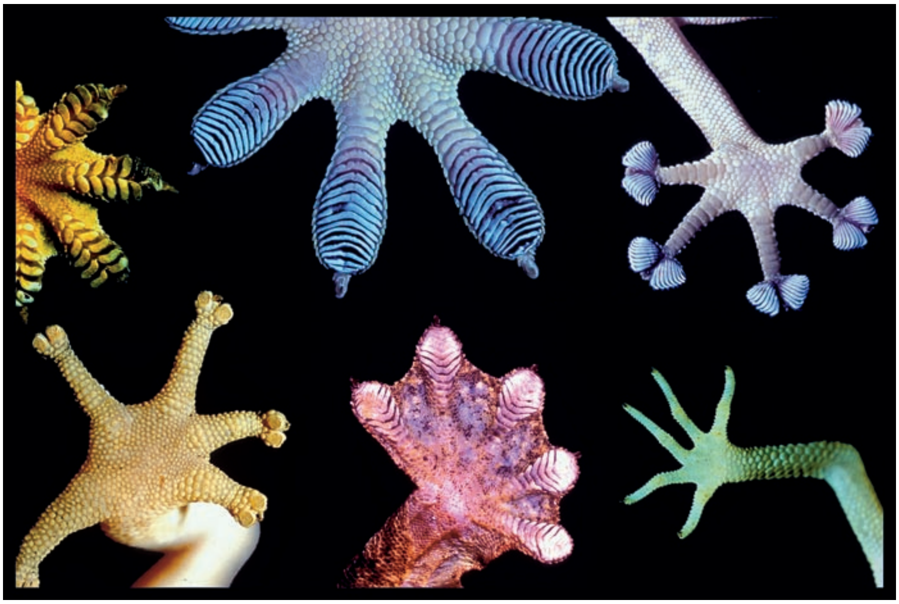

Fig 1 | Geckos have millions of dry, adhesive hairs (setae) on their feet that allow them to stick to nearly any surface. Each seta branches into 100–1,000 flat tips (spatulas) that exploit van der Waals forces to generate adhesion. These chemical bonds temporarily re-arrange electrons and create an electrodynamic attraction. Credit: Kellar Autumn, Lewis & Clark College, Portland, OR, USA.

One example of a natural-design solution that humans are willing to emulate is the ability of geckos to climb walls and ceilings. The gecko's secret lies in the composite structure of its feet, on which every single toe pad is covered with millions of keratinous hair-like bristles called setae (Autumn, 2007). Each seta in turn branches into hundreds of flat tips called spatulas, which make intimate contact with surfaces (Figs 1,2). This fibrillar array—also common in other biological adhesive organs—achieves adhesion primarily by non-covalent van der Waals forces between the spatulas and the surface (Autumn *et al*, 2002), although capillary forces have also been proposed to play a role in some circumstances (Huber *et al*, 2005).

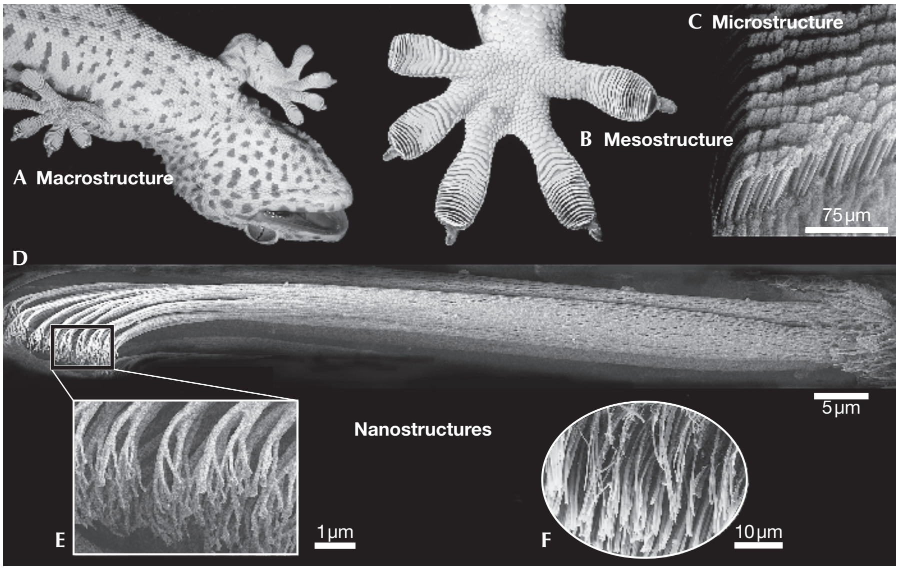

Fig 2 | Structural hierarchy of the gecko adhesive system. **(A)** Ventral view of a tokay gecko (*Gekko gecko*) climbing a vertical glass surface (photo by M. Moffett). **(B)** Ventral view of the foot of a tokay gecko, showing a mesoscale array of seta-bearing scansors, or adhesive lamellae (photo by M. Moffett). **(C)** Microscale array of setae arranged in a nearly grid-like pattern on the ventral surface of each scansor. In this scanning electron microscopy (SEM) image, each diamond-shaped structure is the branched end of a group of four setae clustered together in a tetrad. **(D)** Cryo-SEM image of a single gecko seta (image by S. Gorb & K. Autumn). Note the individual keratin fibrils composing the setal shaft. **(E)** Nanoscale array of hundreds of spatular tips of a single gecko seta. **(F)** Synthetic spatulas fabricated from polyimide using nanomolding at the University of California, Berkeley, USA, in the laboratory of Ronald Fearing. Credit: Kellar Autumn, Lewis & Clark College, Portland, OR, USA.

"Biomimicry of these structures would allow for novel applications in robotics and general temporary adhesive systems," Spolenak said. "[The] [f]irst climbing robots utilizing gecko derived structures, for instance, have already been implemented." However, although there is a huge economic potential for efficient adhesive materials, creating the underlying nanostructures, especially for larger applications, is difficult and expensive. The commercial success of gecko-inspired adhesive structures will therefore depend on developing fast and inexpensive fabrication processes. "If [these] issues can be overcome, [the] technological solutions may be superior to the natural ones. This is due to the fact the natural systems are always as good as they have to be, on one hand, and the choice of materials for technological replicas is much wider than in the natural [world], on the other," Spolenak concluded. A team from the USA recently developed a 'gecko tape' that consists of arrays of carbon nanotubes—replicating the setae-and-spatulas design—attached to a flexible polymer tape, which can withstand shear stresses nearly four times higher than the gecko's foot. The tape sticks to various surfaces including Teflon (Ge *et al*, 2007).

Nature has also developed anti-adhesive surfaces that have attracted much attention from engineers and biologists. The carnivorous plants of the genus *Nepenthes*, for example, have highly specialized pitcher-like leaves that they use to attract, capture and digest insects and other small arthropods (Fig 3). The pitchers contain devices and adaptations that prevent insects from climbing out again, including epicuticular waxy crystals that form slippery surfaces within the pitchers. Elena Gorb's group at the Max Planck Institute for Metals Research in Stuttgart, Germany, has shown how the physicochemical properties of these surfaces influence insect adhesion (Gorb *et al*, 2005). The secret lies in a double layer of crystalline wax, the upper layer of which has crystals that contaminate the insect's adhesive appendages, while the lower layer reduces the contact area between the insect's feet and the plant surface. The insects thus slip ever deeper into the trap where they are digested (Fig 3). "These results provide ideas for further developments of technological non-adhesive surfaces. The principle is recently patented and will be applied in anti-insect foils, anti-adhesive materials and soft-touch surfaces," Gorb said.

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Her colleague Wilhelm Barthlott, Professor of Plant Science at the University of Bonn, Germany, is already forging ahead with the commercialization of naturally inspired non-adhesive surfaces. During the 1980s and early 1990s, Barthlott and his student Christoph Neuhuis took scanning electron microscope pictures of the epidermal surfaces of thousands of plants. Their work revealed that the cleaner the surface of a plant leaf, the rougher it looked in electron microscopy images. In particular, the leaves of the lotus plant (*Nelumbo nucifera*)—which is considered sacred in Buddhist tradition for its blinding whiteness and purity—are densely populated with little bumps. Further investigation showed that dirt particles and water droplets only touch the tops of these nano-sized spikes and drop off owing to a lack of adhesion. Barthlott, while remaining at the university, has commercialized this discovery: dirt-repellent products that emulate the surface of lotus leaves include paint, camera lens coatings, wallpapers and kitchen frontages.

Benyus has proposed two strategies for nature-inspired innovation. The so-called biology-to-design approach begins with understanding a biological phenomenon and then applying it to a human design challenge—Barthlott's discovery of the lotus effect and the design of synthetic dry adhesives based on gecko toe pads are examples of this. By contrast, the design-to-biology approach starts with a design challenge, identifies the core function and then looks to nature to see how various organisms or ecosystems have achieved that function.

Peter Steinberg and Staffan Kjelleberg, both at the University of New South Wales in Australia, literally swam in this direction in the waters of Botany Bay while looking for new compounds to inhibit bacterial growth. "[M]arine organisms such as seaweeds [and] sponges […] live in a bacterial soup […] and are constantly challenged by bacterial colonisation and biofilm formation—the same challenge faced by people when biofilms form on their lungs, catheters, heart valves and other implants […] and industrial surfaces such as water or oil and gas piping, and many other surfaces," Steinberg explained. "A local seaweed—*Delisea pulchra* or delicate beauty—meets this challenge not by producing bacteriocidal chemicals, but rather by producing chemicals which act as antagonists of bacterial signalling, or 'quorum sensing' systems."

These signalling systems, which are broadly distributed across bacterial taxa, control bacterial phenotypes such as biofilm formation, colonization, production of exotoxins and virulence factors—although the specific phenotypes vary between bacteria. Steinberg and his team found that the reason why *Delisea pulchra* remains unfouled is due to a group of secondary metabolites known as halogenated furanones that interfere with bacterial quorum sensing systems (de Nys *et al*, 1995; Hentzer *et al*, 2003). To explore the potential of this finding, they founded the company Biosignal in 1999 to develop and commercialize the signal inhibitors in medical and industrial/domestic applications. "We have progressed as far as animal models in our therapeutics program targeting respiratory infections, initial human safety trials for contact lenses, and have just begun the registration process for compounds targeting biofilms in water treatment," Steinberg said.

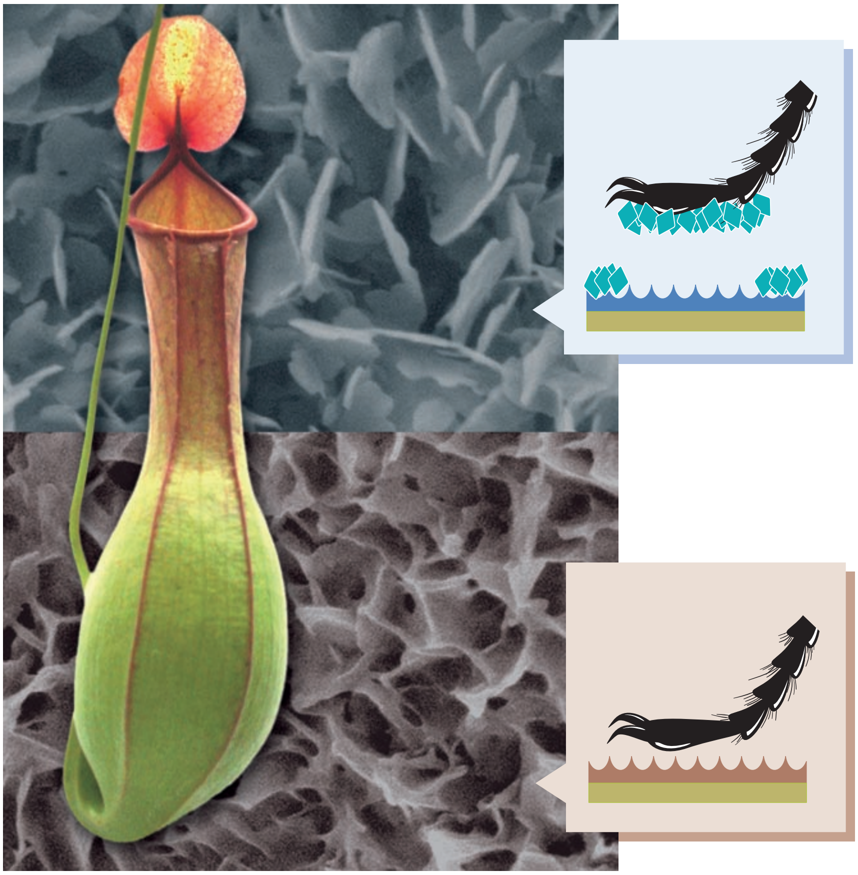

Fig 3 | The pitfall trap of the pitcher plant *Nepenthes alata*. In the background, the image from a scanning electron microscope of the upper and lower wax layers. The diagrams show how the two wax layers reduce the adhesive ability of insects. The upper layer contaminates the adhesive pads of the insect, whereas the lower layer decreases the amount of contact between the adhesive hairs of the foot and the substrate. Credit: Elena Gorb/Max Planck Society.

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Biofilms might be responsible for more than 65% of human bacterial infections and are a serious problem in industrial facilities; they are also notoriously resistant to standard antibiotics or biocides. "Our strategy is to specifically target the biofilm mode of existence using this biomimetic, signal-blocking technology," concluded Steinberg. An additional advantage of this strategy is that it does not kill the bacteria and therefore puts less selective pressure on them to develop resistance.

Another important frontier for biomimicry is the development of advanced optical systems to imitate the various biological optical structures that have evolved naturally (Lee & Szema, 2005). Luke Lee's group at the University of California, Berkeley, USA, recently constructed an artificial compound eye that looks and works like that of an insect (Jeong *et al*, 2006). An insect's eye consists of thousands of integrated optical units called ommatidia that are arranged spherically along a curvilinear surface with each unit pointing in a different direction (Fig 4). The many lenses and curved shape of an insect's eye provide a wide field of view, and extremely fast motion detection and image recognition. Lee's group used flexible polymers to build artificial ommatidia, each with a tiny lens connected to a tube-like waveguide to direct the light on to an optoelectronic imaging device. They then arranged these artificial ommatidia around a dome to project outwards (Fig 5). Miniaturized cameras and motion sensors based on such lenses could have medical, industrial and military applications, such as data storage and readout, medical diagnostics, surveillance imaging and light-field photography (Jeong *et al*, 2006).

Biomimicry is not just a fertile ground for biologists and engineers, it is also part of a larger environmental movement. "I think of biodiversity as a massive design library. There are millions of species,

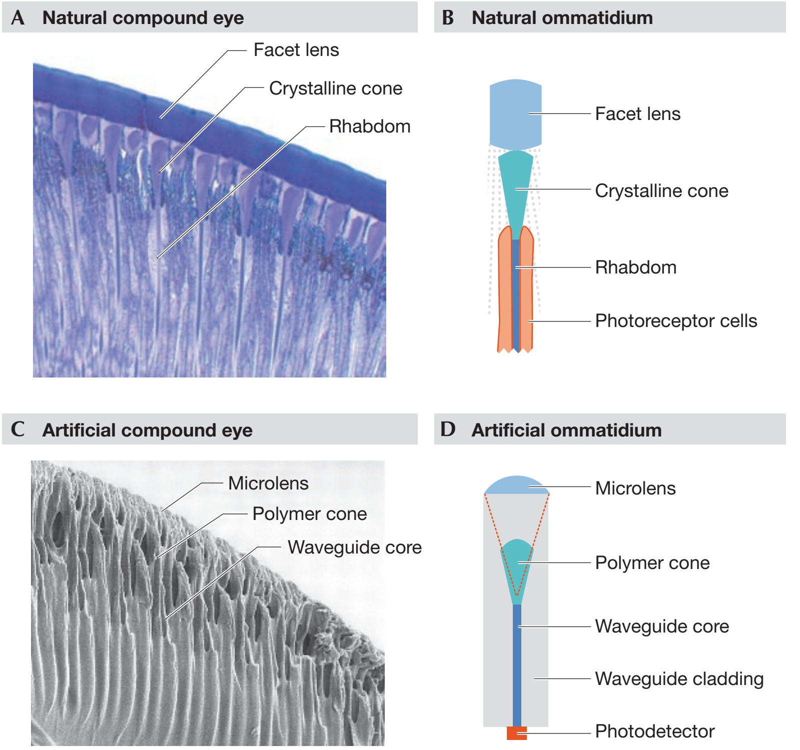

Fig 4 | Anatomical comparisons between a natural compound eye and an artificial compound eye, as described from cross-sections. (**A**) An optical micrograph of a honeybee's apposition compound eye (courtesy of B. Greiner). As an individual optical unit, (**B**) a natural ommatidium consists of a facet lens, a crystalline cone and photoreceptor cells with a wave-guiding rhabdom. (**C**) A scanning electron micrograph of an artificial compound eye and (**D**) an artificial ommatidium comprising a microlens, a polymer cone and an optical waveguide that has a higher index core surrounded by a lower index cladding in a polymer resin. Light hitting a microlens is coupled with polymer cones and waveguides, and then guided onto photodetectors at the end of the waveguide. Image from Jeong *et al* (2006). Reproduced with permission from American Association for the Advancement of Science, Washington, DC, USA.

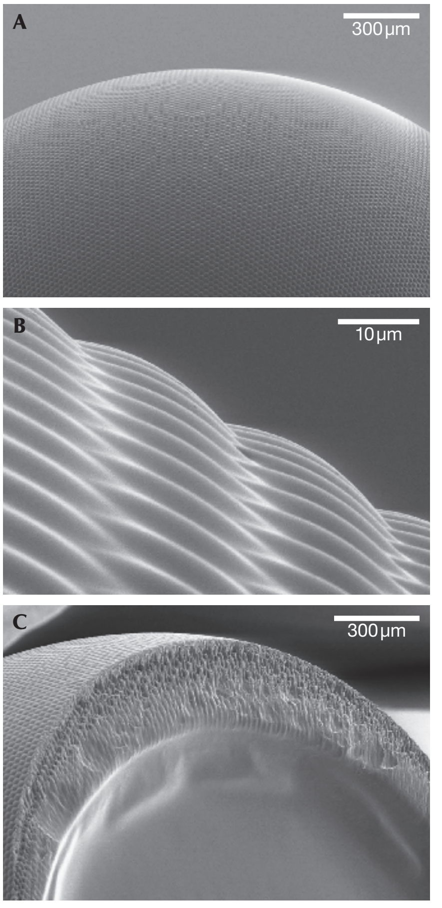

Fig 5 | Microstructure of a biomimetic artificial compound eye. (**A**) The spherical arrangement of 8,370 artificial ommatidia on a hemispherical polymer dome 2.5 mm in diameter. (**B**) Hexagonal microlenses. (**C**) A cross-section of the artificial eye with the spherical arrangement of artificial ommatidia consisting of microlenses, polymer cones, and waveguide arrays. Image from Jeong *et al* (2006). Reproduced with permission from American Association for the Advancement of Science, Washington, DC, USA.

each with different solutions to nature's problems, each with secrets that are waiting for us. But the scary thing is that extinction is taking these 'books'—species—off the shelves and burning them faster than we can open them and read them. Even if all we care about is economic progress, we need to slow the rate of extinction before these secrets of nature are lost forever," said Kellar Autumn, Associate Professor of Biology at Lewis & Clark College, Portland, OR, USA.

Proponents of biomimicry hope that it could help to solve some of the major problems created by the global growth of industrialization and the exploitation of natural resources. Many of these impulses come from the Biomimicry Institute in the USA, with similar initiatives appearing in Europe. "Biomimicry Europa wants to contribute to the quest for other routes by promoting biomimicry as a key tool to develop innovative and positive solutions directed towards sustainability," said Gauthier Chapelle, General Secretary of Biomimicry Europa (Brussels, Belgium). According to Chapelle, the inventory of European biomimicry projects held by his organization currently has more than 100 entries, with universities in UK and Germany among the most active players.

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Starting with this premise, it is possible that biomimicry—perhaps coupled with the concept of industrial ecology, which adopts nature as a model for optimal material and energy flow—will change the industrial production system. "We very much believe that the biomimicry approach will grow significantly and, eventually, will be universally adopted across all industries. In my many years of working in the area of sustainability, biomimicry is the only tool I have found that is applicable in all design situations and—if done properly—can always lead to sustainable results," said Denise DeLuca of the Biomimicry Institute. "It is the only tool

I have found that can get us out of this box canyon we have [gotten] ourselves into. Since the industrial revolution, we have used our incredible intelligence to develop technologies and global economies based on fossil fuels and toxic chemicals, which are clearly non-sustainable. We have to find other ways." In addition, DeLuca noted that biomimicry has the added benefit of making people look at nature differently—as a source of innovation rather than simply a source of raw materials. "Biomimicry enables people to generate amazing creative and [innovative] designs inspired by nature, even if sustainability is not a primary goal," she said.

However, not everyone shares this view. "I'm still ambivalent as to whether biomimicry is an environmentally correct marketing ploy that promises more than it will be able to deliver, or the inadvertent rediscovery of practices that are as old as human creativity," said Pierre Desrochers, an expert in sustainable economic development and technological innovation at the University of Toronto Mississauga in Canada. He believes that we already owe many of our present technologies to inspiration from nature. "The problem, as I see it, is that there is often a world of experimentation between a basic idea or a promising lab result and the 'scaling up' of those into commercially viable production operations or systems," he said. "Biomimics should remember Thomas Edison's famous dictum that invention (or genius) is 1% inspiration and 99% perspiration. I'm afraid that many of them don't see much beyond the 1%. Having ideas or being inspired by nature is a nice thing, but it's only a first step. Much work needs to be done afterwards and this probably explains why we do things the way we do them now rather than simply copy things as we see them in nature."

Although the road from the inventor's mind to the real world is rarely clear, some of those who draw inspiration from nature are aware that simple imitation alone is not necessarily the way forward, rather combining naturally inspired design and human inventiveness. "Imitating nature is a complex endeavour, and a blind biomimetic approach is not the best methodology," Luke Lee and Robert Szema wrote in *Science*. "However, if we are able to decode the designs, then the combination of our creativity in materials and nature's wisdom is a synergistic one with incredible potential" (Lee & Szema, 2005).

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doi:10.1038/sj.embor.7401107